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We analyze the effects of an in-medium broadening of nucleon resonances on the exclusive photoproduction of mesons on nuclei as well as on the total photoabsorption cross sections in a transport calculation. We show that the resonance widths observed in semi-inclusive photoproduction on nuclei are insensitive to an in-medium broadening of nucleon resonances. This is due to a simple effect: the sizeable width of the nuclear surface and Fermi motion.

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One of the most obvious in-medium effects is the observed disappearance of the resonance structures in the second and third resonance region in the total photoabsorption cross section on nuclei [1]. Kondratyuk et al. [2] and Alberico et al. [3] have shown that this disappearance can be explained by an extra in-medium width of about 0.3 GeV for the higher resonances. Two reasons for this large width have been discussed. In [4,5] we have pointed out that the total in-medium width of the  $D_{13}(1520)$  resonance could reflect a lowering of the  $\rho$  meson spectral strength. A lowering of the  $\rho$  meson strength has been predicted by various hadronic models and QCD sum rule analyses (for a summary and review see [6]). Also effects of collisional broadening of this resonance due to collisions with other baryons have been considered [2–4]. Both effects lead in lowest order in the density to an extra in-medium resonance width that is proportional to the nuclear density  $\rho$  [4,5,7].

In a recent paper Krusche et al. [8] discuss their data on inclusive and semi-inclusive single  $\pi^0$  production in the second resonance region. After subtracting a smooth background from the observed cross section these authors obtain a resonance contribution which they attribute to the  $D_{13}(1520)$  nucleon excitation. This resonant part shows a width that is compatible with the free width of the  $D_{13}(1520)$  when smeared over the Fermi momentum of the nucleons in the target nucleus (see Fig. 5 in [8]). This result seems to present a problem for explanations of the disappearance of this resonance in the photoabsorption experiments [1] in terms of an in-medium broadening of the  $D_{13}$  resonance. Raising this problem has been the

central point of Ref. [8].

In this letter we show the first analysis of these data in a transport theoretical coupled channel BUU (CBBU) calculation. The results of this calculation exhibit a remarkable, unexpected insensitivity of the width of the resonant contribution to the single  $\pi^0$  cross section to the strength of the in-medium broadening. We then present a very simple explanation of this observation. The purpose of this letter is not to provide a perfect reproduction of the data of [8], but instead to help solving the apparent dilemma raised in Ref. [8].

We start out by presenting results of a CBBU calculation based on the method explained in detail in [4,5,10]. The calculations use a spectral function for the nucleon resonance in the relativistic form

$$A(s) = \frac{s\Gamma_{\text{tot}}(s)}{(s - M^2)^2 + s\Gamma_{\text{tot}}^2(s)} . \quad (1)$$

Here  $M$  is the resonance mass and  $\Gamma_{\text{tot}}$  its total width, which is given as a sum over the total decay width and an in-medium, density-dependent width  $\Gamma_{\text{med}}$

$$\Gamma_{\text{tot}} = \Gamma_{\text{decay}}(s) + \Gamma_{\text{med}} . \quad (2)$$

The in-medium width for the  $D_{13}(1520)$  resonance is taken as

$$\Gamma_{\text{med}} = \Gamma_m \frac{\rho(r)}{\rho_0} , \quad (3)$$

as is, e.g., appropriate for a width that originates in two body collisions of the resonance with nucleons in the nuclear medium. Actually, the precise mechanism that leads to this density dependent width is irrelevant for the arguments to follow; also the mechanism described in the first paragraph ( $\rho$  mass lowering) leads in lowest order to a width proportional to the density  $\rho$ . The calculations have been done both with and without this in-medium width. Increasing the width parameter  $\Gamma_m$  both broadens the resonance and lowers its amplitude.

The lowering can clearly be seen in Fig. 1, where we show the results of this calculation for semi-inclusive single  $\pi^0$  production in comparison to the data of Ref. [8], and in Fig. 1 of Ref. [8] where a comparison of total inclusive  $\pi^0$  photoproduction data with transport calculations from [5] is shown for various medium modified widths.

It is seen that the data in the second resonance region are described reasonably well with an in-medium width parameter  $\Gamma_m = 0.3$  GeV [2]; the disagreement

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at the lower energies is due to the neglect of two-body absorption with  $\Delta$  degrees of freedom in the calculation [4]. The value  $\Gamma_m = 0.3$  GeV is hard to justify for a collisional width alone (as discussed in [4,5]); it serves in this context only as an example for a strong medium modification and represents the summed effect of a  $\rho$  meson mass shift, collisional broadening and possibly other density dependent effects.

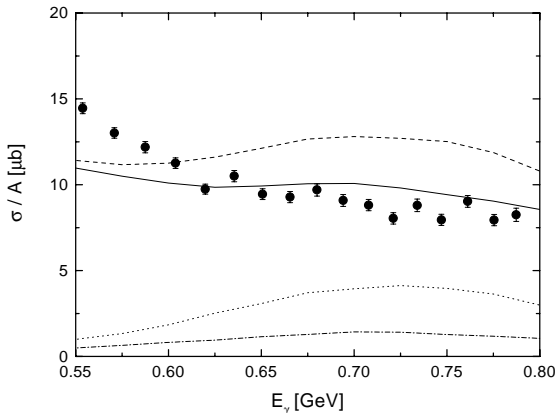


FIG. 1. Calculated cross section for semi-inclusive single  $\pi^0$  photoproduction on  $^{40}\text{Ca}$  in comparison to the data of [8]. The same missing energy cuts as in [8] have been applied. Shown are results both without (dashed) and with an in-medium broadening ( $\Gamma_m = 0.3$  GeV) (solid line) and the contribution of the  $D_{13}(1520)$  alone for both widths (dotted and dash-dotted lines).

In the CBUU calculation we can actually follow the history of the emitted pions and can thus determine which of the observed pions were emitted last by a  $D_{13}(1520)$  resonance. The lower curves in Fig. 1 show this contribution with and without this in-medium broadening. It can be seen that in the calculation including the broadening only a very small part ( $\sim 10$ – $20\%$ ) of all single  $\pi^0$  in this mass region stems from the  $D_{13}(1520)$  decay; there is a much larger contribution from other sources (mainly  $P_{33}(1232)$ ,  $S_{11}(1535)$  decay and nonresonant background). This is so although in this energy range the  $D_{13}(1520)$  resonance is dominant for absorption of real photons on free nucleons, so that the first  $(\gamma, \pi)$  reaction proceeds preferably through this resonance. However, because of the in-medium broadening, this dominance of the  $D_{13}(1520)$  has disappeared in the asymptotic yield.

We now analyze the shape of the resonance contribution. Fig. 2 shows the single  $\pi^0$  cross section from the  $D_{13}(1520)$  alone (lower curves in Fig. 1) in some more detail. As already seen, the cross section drops when the in-medium width is increased to 0.3 GeV. However, the shape of the single  $\pi^0$  cross section as a function of the photon energy does not change significantly when the collisional width is increased. This – at first sight – surprising result implies that in this calculation the total

width of the single  $\pi^0$  production excitation function is insensitive to collisional broadening.

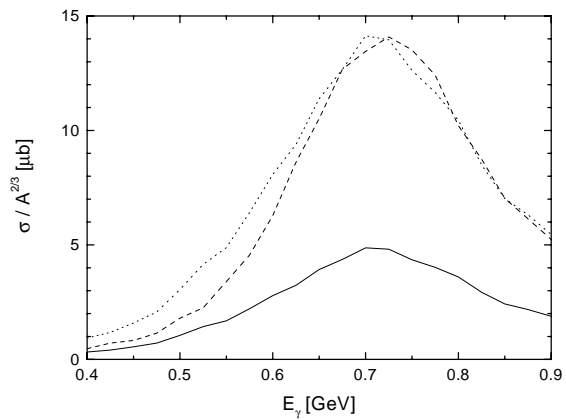


FIG. 2. Contribution of the  $D_{13}(1520)$  to the semi-inclusive single  $\pi^0$  yield in  $^{40}\text{Ca}$  without (dashed line) and with (solid line) 0.3 GeV in-medium broadening. The dotted line is identical to the solid line, but scaled up by a factor 2.9 in order to facilitate the comparison of the widths.

A first guess to explain this behavior is obviously ascribing it to final state interactions. The pions experience strong reabsorption so that the observed pions can be expected to originate somewhere in the surface region of the nucleus. The observed  $A^{2/3}$  dependence of the single pion cross section [8] seems to substantiate this explanation.

We now show, however, that even without reabsorption the width of the observed resonance distribution is insensitive to an in-medium broadening of nucleon resonances whereas, on the contrary, total absorption cross sections directly reflect this broadening.

We write the cross section for the primary production of single pions from nuclei as a function of incoming photon energy  $E_\gamma$  by simply folding the elementary  $(\gamma, \pi)$  cross section on the nucleus with the nuclear phase space distribution in the Thomas-Fermi approximation. This gives [10]

$$\sigma_\pi(E_\gamma) \sim \int_{\text{NV}} dr r^2 \int_0^{p_F(r)} d^3p \Gamma_\gamma(s(E_\gamma, \vec{p})) \times A(s(E_\gamma, \vec{p})) \frac{\Gamma_\pi(s(E_\gamma, \vec{p}))}{\Gamma_{\text{tot}}(s(E_\gamma, \vec{p}))}. \quad (4)$$

Here  $\Gamma_\gamma$  is the in-width of the incoming photon [11],  $\Gamma_\pi$  the one pion decay width, and  $s$  is the square of the invariant resonance mass. The  $s$  dependences of  $\Gamma_\pi$  and  $\Gamma_{\text{decay}}$  are taken from the analysis of Manley et al. [9]. The momentum space integral runs over the ground state nucleon momenta up to the local Thomas-Fermi momentum  $p_F(r)$  and the  $r$  space integral extends over the nuclear volume. The cross section (4) does not contain any final state interactions of the produced pions, which

are automatically contained in the BUU results shown in Fig. 1.

We now analyze the resonance shape of the cross section (4) as a function of the in-medium width parameter  $\Gamma_m$ . We perform the calculations for the nucleus  $^{40}\text{Ca}$  with a density distribution of the Woods-Saxon type with parameters given in [5].

In Fig. 3 we show the observed full width  $\Gamma_{\text{peak}}$  of the resonance in the one pion photoproduction cross section  $\sigma_\pi(E_\gamma)$  as a function of the in-medium width  $\Gamma_m$ . The figure contains results of a calculation both with Fermi motion included and without. It is seen that the resonance width as a function of the in-medium width first increases in both cases, as expected. However, in both cases the widths actually level off as a function of  $\Gamma_m$ ; the realistic case with Fermi motion of the nucleons included rises by about 10% from 0.3 GeV for  $\Gamma_m = 0$  up to about 0.33 GeV at  $\Gamma_m = 300$  MeV and then stays roughly constant. This change is so small that it cannot be observed in the data.

This behavior is a direct consequence of the form of the cross section (4) and, more specifically, the density dependence of the in-medium width  $\Gamma_{\text{med}}$  (3). The  $\rho$  dependence of the in-medium width in Eqs. (3) and (4) leads, through its lowering of the amplitude, to a decrease of contributions from the nuclear interior. This decrease is stronger closer to the center of the nucleus and weaker farther out. Thus, increasing the in-medium width parameter  $\Gamma_m$  in (3) effectively moves the region of highest sensitivity out from the maximum of  $\rho(r)r^2$  to even larger radii with smaller density, so that the observed in-medium width stays approximately constant. In a (fictitious) nucleus with constant density the total width does not level off, but increases with  $\Gamma_m$ ; the same holds if the in-medium width does not depend on density.

We note that the detailed form of the  $s$  dependence of the total decay and pion widths  $\Gamma_{\text{decay}}$  and  $\Gamma_\pi$  is not essential for this result. Taking constant values for both widths also leads to a levelling off, although at a somewhat higher value, of the total width. Thus, purely geometrical effects alone lead to the observed near independence of the resonance width on the in-medium width; the reabsorption neglected in (4) can only enhance this behavior since it also acts to shift the 'sensitivity region' further out.

Semi-inclusive meson photoproduction experiments are thus nearly insensitive to an in-medium broadening of the nucleon resonances as far as their shape is concerned; only their amplitude is diminished. On the contrary, the width of the resonant part of the total photoabsorption cross section is quite sensitive to an in-medium broadening. In this case, Eq. (4) has to be modified such that the factor  $\Gamma_\pi$  in the integrand in (4) is replaced by  $\Gamma_{\text{tot}}$ , which includes as one of its terms the width  $\Gamma_{\text{med}}$  (see (3, (2))). For large  $\Gamma_{\text{med}}$  this latter term becomes dominant and counteracts the corresponding term in the denominator of the Breit-Wigner distribution in (4). Indeed, when plotting the observed width of the absorption cross

section vs.  $\Gamma_m$  one finds a continuous increase without any levelling off (see Fig. 3, dotted line).

The broadening of nucleon resonances can thus be seen in the photoabsorption experiments, but not in the more exclusive pion production experiments. Also, a somewhat larger effect of in-medium broadening remains in the invariant mass distribution of the resonance, constructed from its decay products, because here the Fermi motion effect is absent (see dashed curve in Fig. 3) and the width in the  $\sqrt{s}$  distribution can directly be seen.

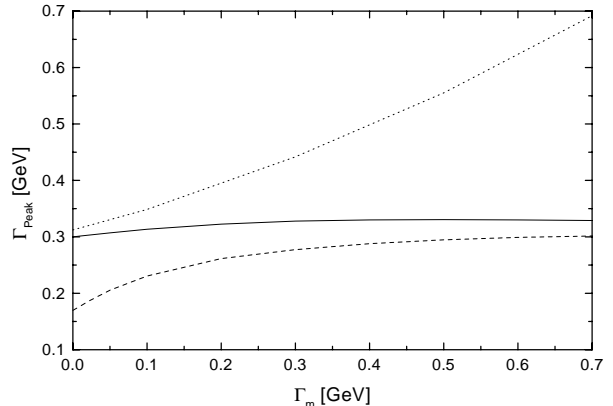


FIG. 3. Full width at half maximum of the photoproduction cross section for single pions (4) for  $^{40}\text{Ca}$  as a function of the in-medium width  $\Gamma_m$ . The solid line gives the calculation with Fermi motion included, the dashed line that without Fermi motion. Also shown is the total FWHM for the photoabsorption cross section (dotted).

Of course, all different reaction channels on the nucleon are determined by one and the same total width of the resonance. However, in experiments with nuclei the different reactions sample the resonance at different densities and thus see different total widths. This different sensitivity of the semi-inclusive and the fully inclusive processes is a simple consequence of nuclear geometry. This finding is in line with the empirically observed  $A$  dependence of the cross sections. Whereas photoabsorption cross sections scale with  $A$  for nuclei heavier than Carbon [1], the semi-inclusive and inclusive  $\pi^0$  cross sections scale with  $A^{2/3}$  [8], thus indicating a volume and a surface effect, respectively.

Finally, we mention that the width of the density averaged spectral function  $A(s)$  increases with  $\Gamma_m$ , but considerably more slowly than that of the absorption cross section. In addition, it is free of any Fermi motion effects. Experiments that reconstruct the invariant mass distribution are, therefore, sensitive to in-medium broadening, if the final state interactions can be neglected.

In summary, the width of the resonant part of the semi-inclusive single  $\pi^0$  photoproduction in the second resonance region is found to be insensitive to an in-medium broadening of the resonance, in contrast to photoabsorp-

tion. This explains the results of Ref. [8] and solves the apparent problem discussed there. It also has an important implication for planned photoproduction experiments on nuclei that are motivated by the search for in-medium changes of hadronic properties.

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